Wavelength Dependence of Lithography Resolution in Extreme Ultraviolet Region

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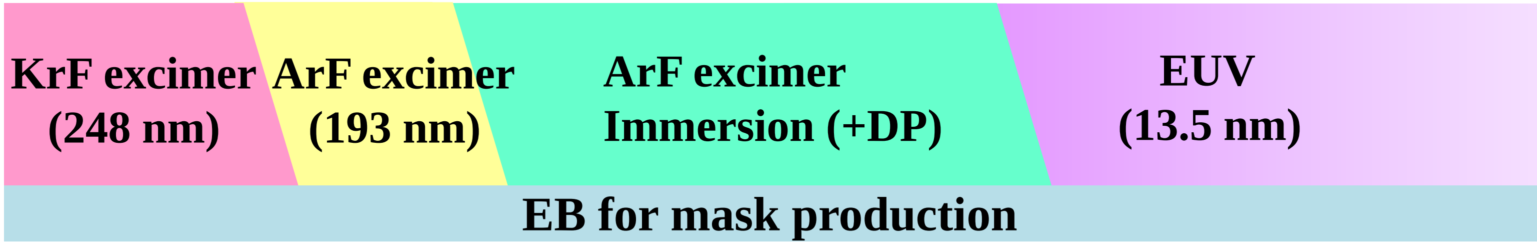
ITRS2010 Update

Lithography Roadmap

Year	2001	04	07	10	13	16	19	22
Line width (nm)	130	90	65	45	32	22	16	11
LWR (nm)					2.2	1.6	1.1	0.8

Lithography Solution



KrF excimer (248 nm)

ArF excimer (193 nm)

ArF excimer Immersion (+DP)

EUV (13.5 nm)

EB for mask production

Wavelength reduction vs. High NA

In EUV wavelength region, photoelectrons sensitize acid generators.

○ The energy of photoelectrons increases with the reduction of wavelength, namely, the increase in photon energy.

The resolution blur caused by photo- and secondary electrons will increase with the reduction of wavelength.

○ The effect of inner shell excitation will appear.

Objective

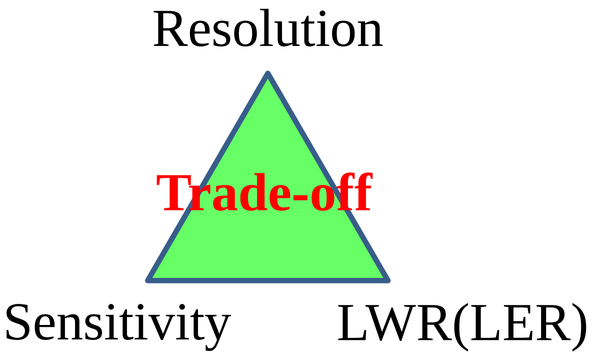
The dependence of resolution blur and quantum efficiency on the wavelength of the exposure tool was theoretically investigated.

On the basis of the simulation results, the extendibility of projection lithography is discussed from the viewpoint of resolution and sensitivity.

Problems in resist material design for short wavelength EUV are discussed.

Acid diffusion length does not depend on the wavelength of exposure tools.

Excluded from discussion



Resolution

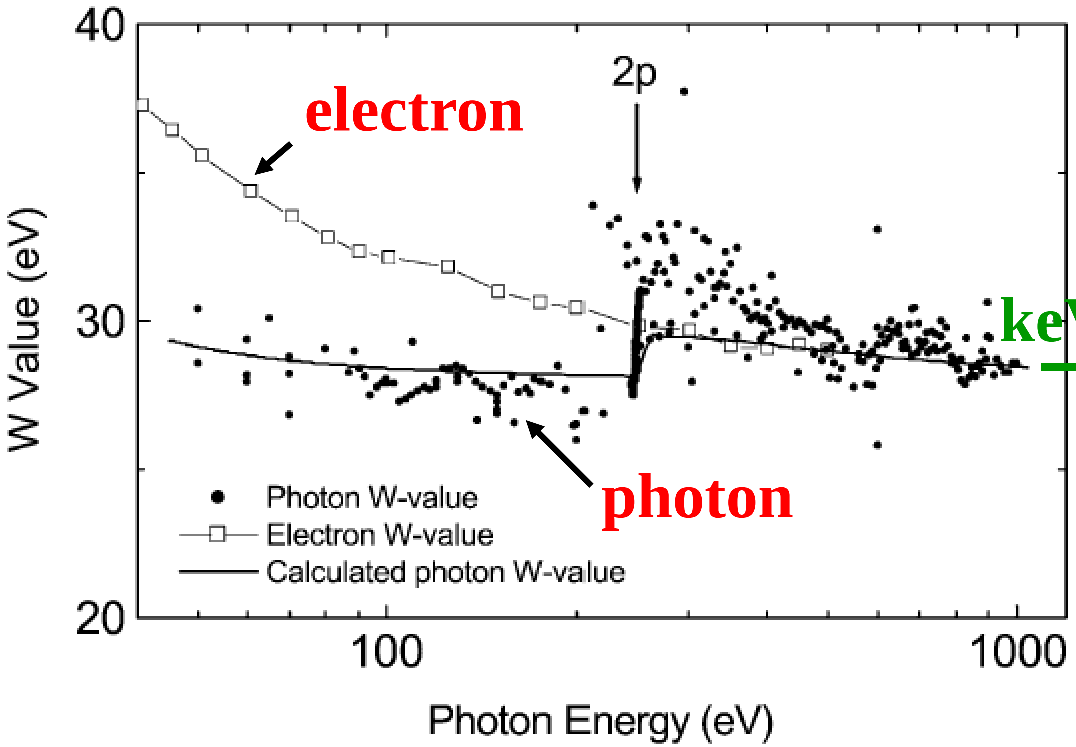
Trade-off

Sensitivity

LWR(LER)

LWR was also excluded because the effect of wavelength on LWR is too complicated to be discussed here. (The effect of wavelength on sensitivity is more important.)

Average energy required to produce an ion pair (W-value)



$$\text{W-value} = \frac{100\ (\text{eV})}{\text{G-value}}$$

keV —————— **MeV**

Insensitive to quality and energy for radiations above keV

K-edge

Carbon: 284 eV

Oxygen: 547 eV

Fig. Photon W-value for Ar as a function of photon energy. The solid circles show the present result, and the open squares are the data of Combecher for electrons. The solid curve represents the photon W-values calculated by the model here. The arrow indicates the 2p ionization threshold. [N. Saito, I. H. Suzuki, Radiat. Phys. Chem. 60, 291 (2001).]

W-value in PHS

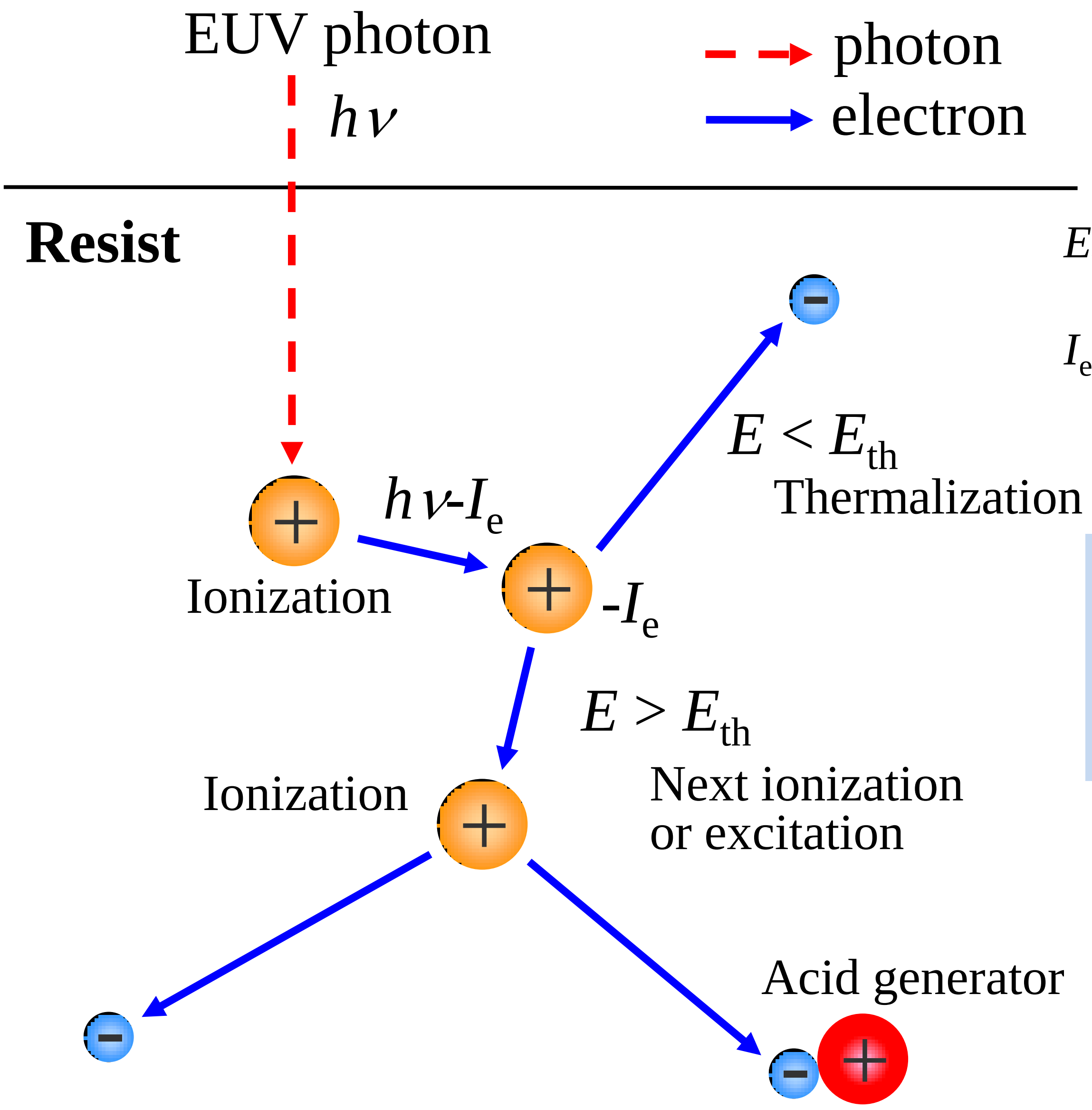
22.2 eV (75 keV EB)

[JVST B24, 3055(2006)]

Average number of secondary electrons per EUV photon = $h\nu/22.2$

(92.5/22.2 = **4.2**)

Sensitization mechanism of EUV resists



EUV photon

$h\nu$

photon

electron

Resist

$h\nu$-I_e

Ionization

-I_e

$E < E_{th}$

Thermalization

$E > E_{th}$

Next ionization or excitation

Ionization

Acid generator

E_{th}: Threshold energy for electronic excitation

I_e: Ionization energy

Simulation processes

(1) Absorption

(2) Deceleration

Wavelength dependent

$E_{th} < E < h\nu\text{-}I_e$

(3) Deceleration

25 meV $< E < E_{th}$

(4) Electron diffusion and reaction

E=25 meV

Activation energy for dissociative electron attachment : ~0

The electron with thermal energy can sensitize acid generators.

Wavelength dependence of absorption coefficient

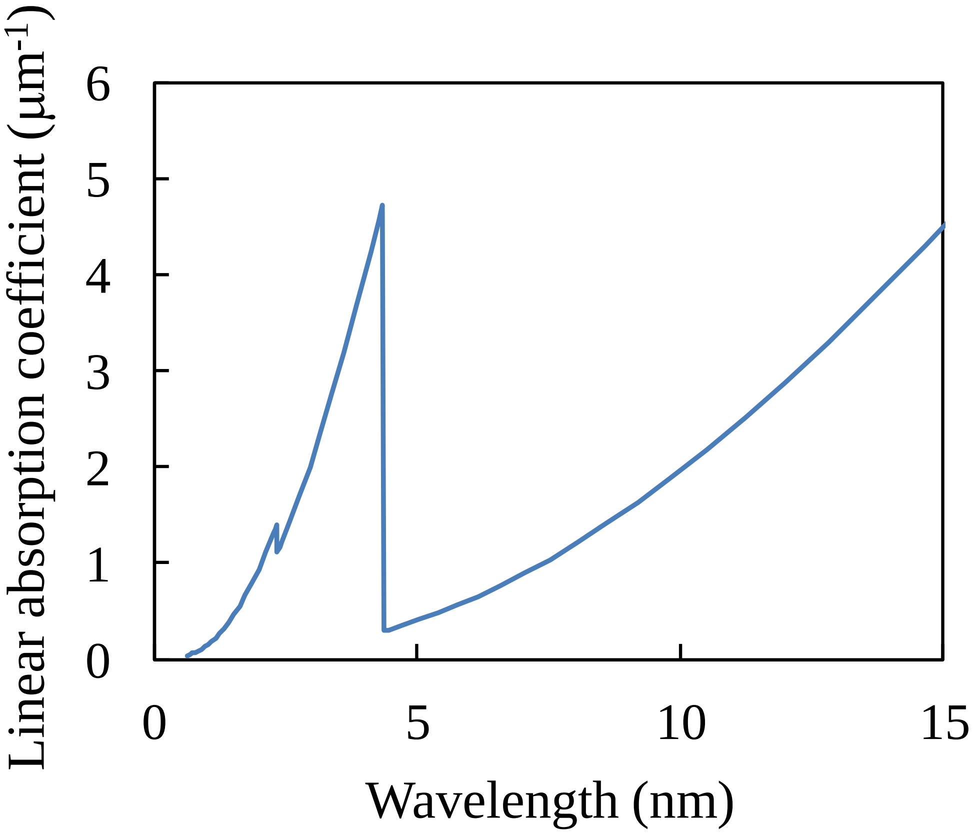
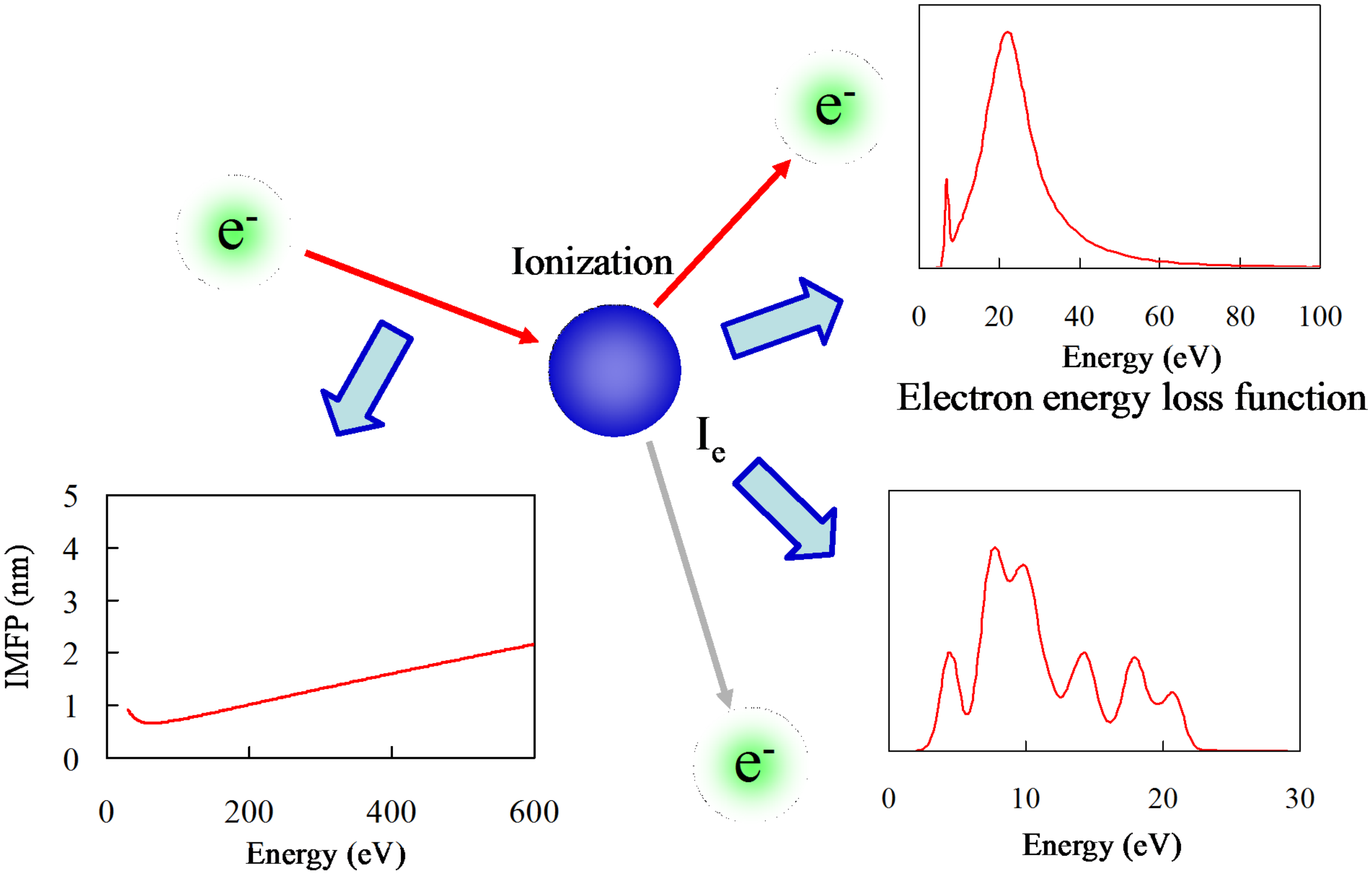


Fig. The linear absorption coefficient of PHS calculated using the X-ray form factor, attenuation, and scattering tables provided by the National Institute of Standards and Technology (NIST).

Formulation ($E > E_{th}$)

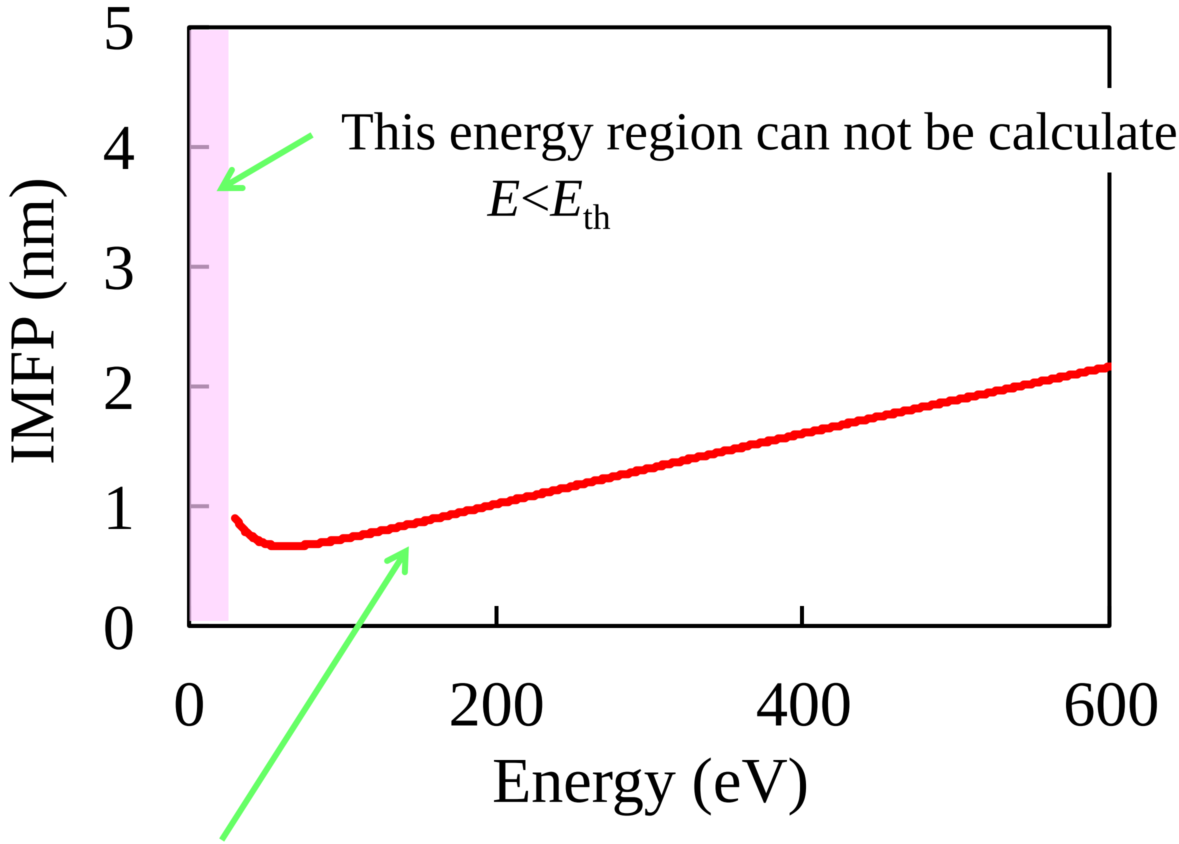

e-
Ionization
e-
I_e
e-
5
4
3
2
1
0
IMFP (nm)
0
200
400
600
Energy (eV)
0
20
40
60
80
100
Energy (eV)
0
10
20
30
Energy (eV)

Electron energy loss function

Inelastic mean free path

Photoelectron emission spectrum

Inelastic mean free path (IMFP) of electron



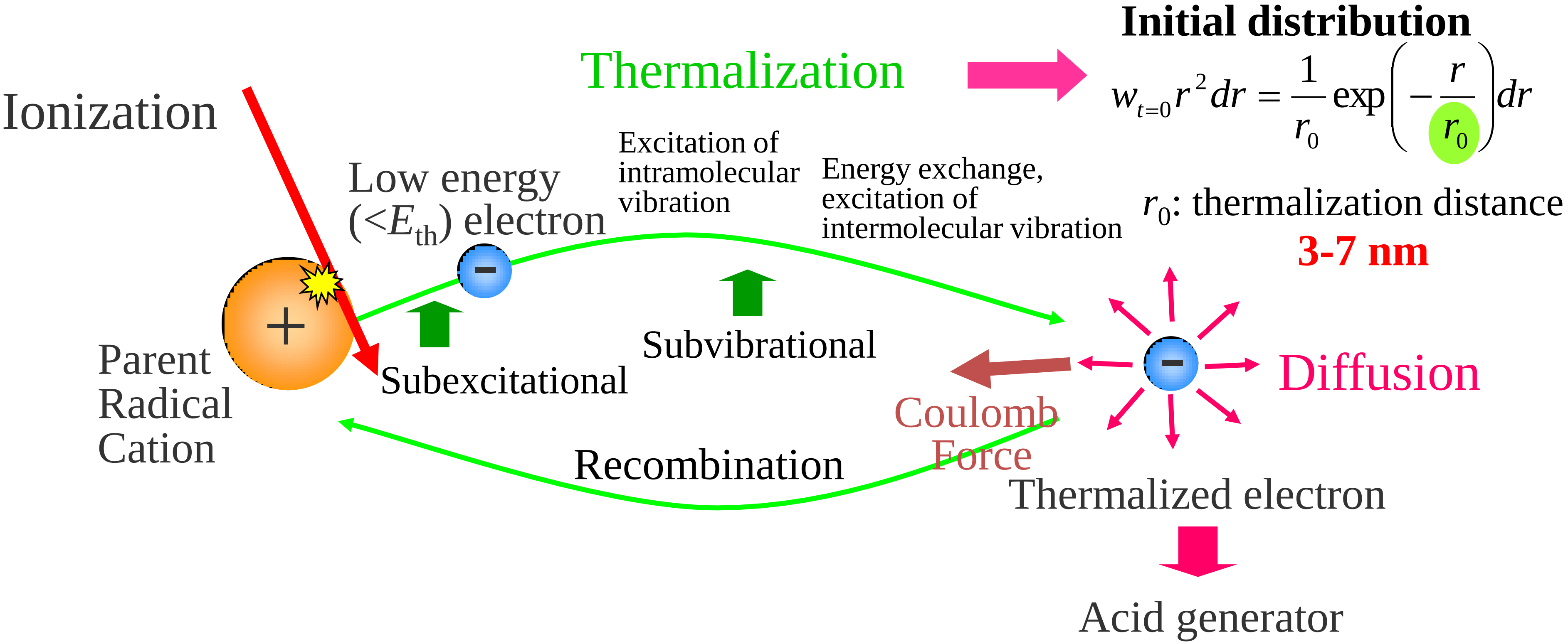
This energy region can not be calculated.

$E<E_{\mathrm{th}}$

Modified form of Bethe equation applicable to ~20 eV

$$\lambda = \frac{E}{\left\{E_p^2\left[\beta\ln(\gamma E)-\left(\frac{C}{E}\right)+\left(\frac{D}{E^2}\right)\right]\right\}}$$

Formulation ($E<E_{th}$)



Initial distribution

$$w_{t=0} r^2 dr = \frac{1}{r_0}\exp\left(-\frac{r}{r_0}\right)dr$$

r_0: thermalization distance

3-7 nm

Thermalization

Ionization

Low energy ($<E_{th}$) electron

Excitation of intramolecular vibration

Energy exchange, excitation of intermolecular vibration

Parent Radical Cation

Subexcitational

Subvibrational

Coulomb Force

Diffusion

Recombination

Thermalized electron

Acid generator

Trajectories of thermalized electrons were calculated using Monte Carlo method.

If the electron reached a radical cation within the distance of r_+, the electron was regarded to be lost through the recombination.
If the electron reached an acid generator molecule within the distance of r_{AG}, the electron was regarded to induce the dissociation of that acid generator molecule.

Thermalization distance in PHS

T. Kozawa et al., Jpn. J. Appl. Phys. 50 (2011) 030209.

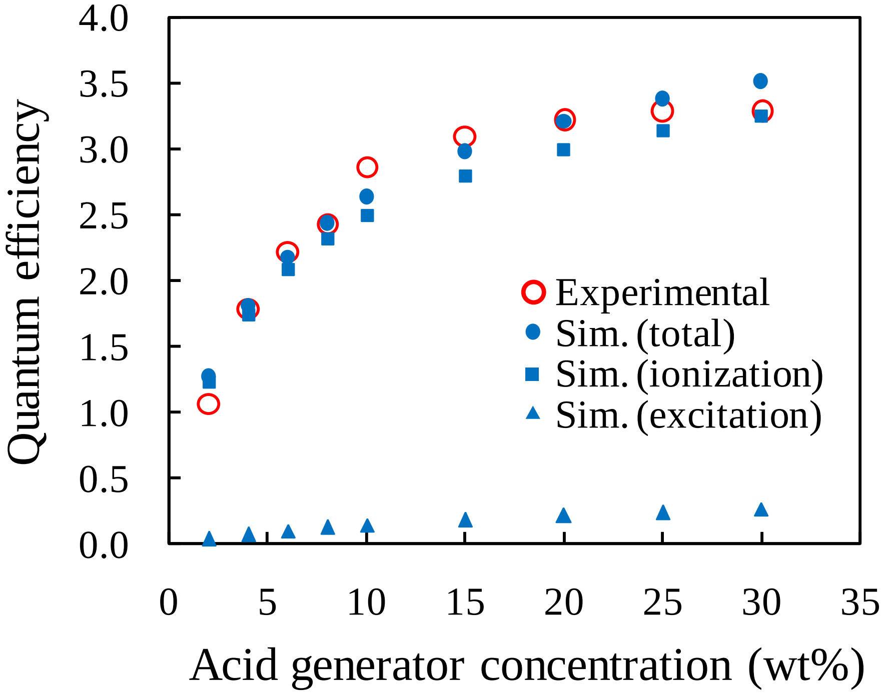


Fig. Quantum efficiency of acids generated in PHS films with TPS-tf upon exposure to EUV radiation

PMMA: ~6nm

Typical PHS type resist with alkyl protected unit : ~4nm

Acrylate type resist : ~6nm

Analysis with Monte Carlo simulation

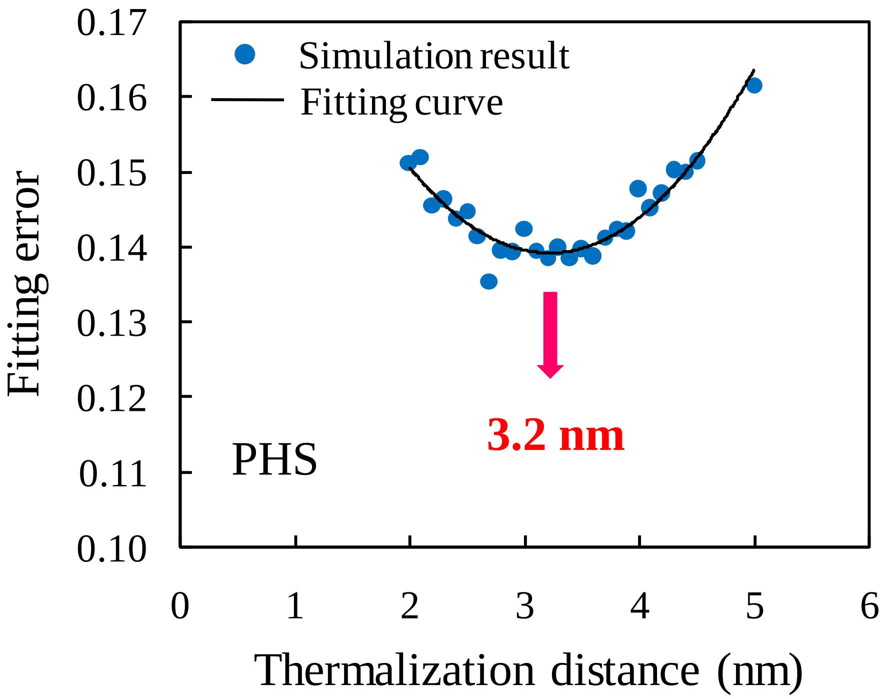
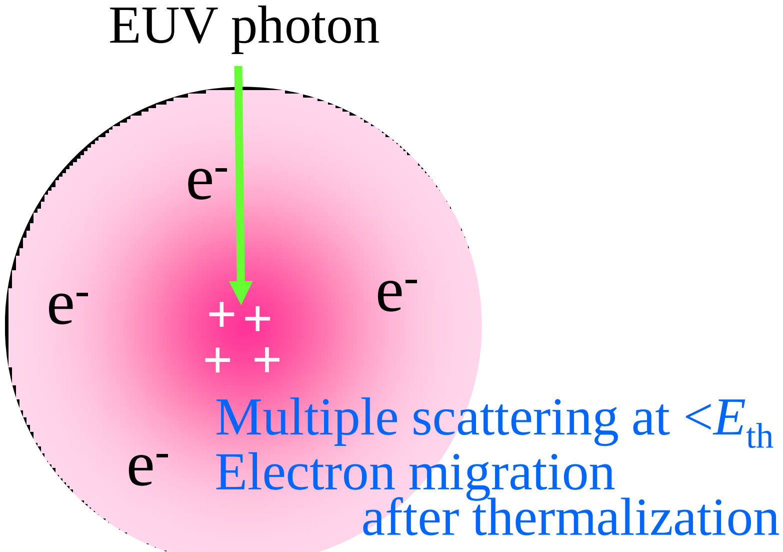


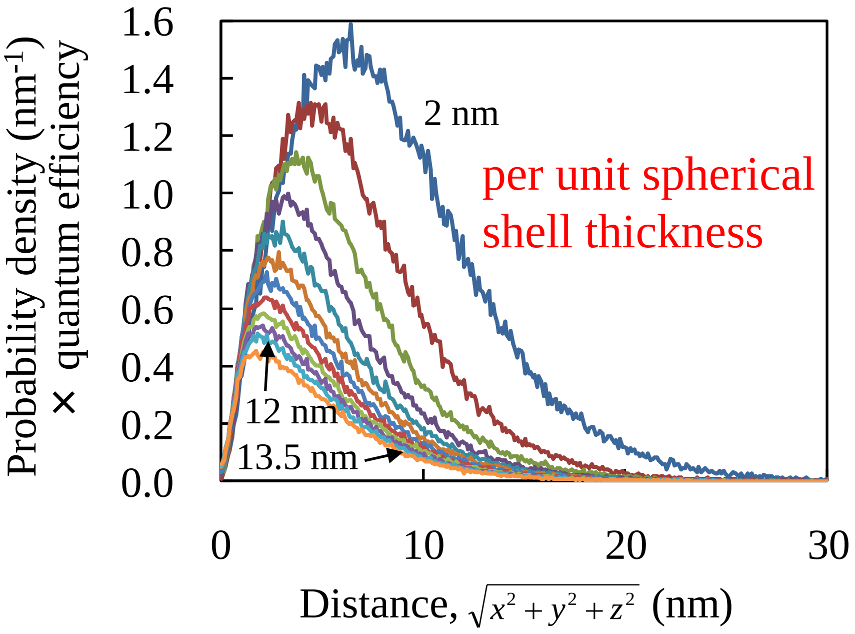
Fig. Relationship between fitting error and thermalization distance

Wavelength dependence of resolution blur caused by secondary electrons

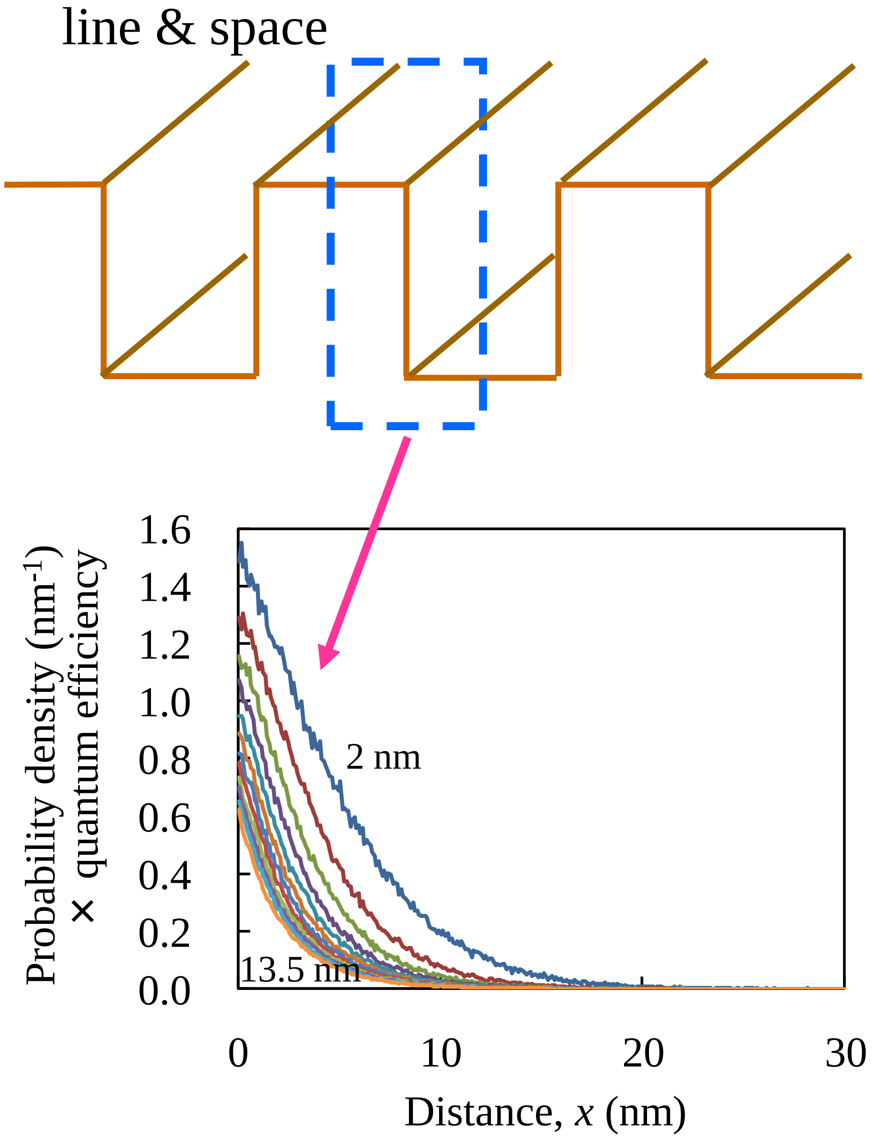


Multiple scattering at $<E_{\mathrm{th}}$
Electron migration
after thermalization

Spherically symmetric



Spherical coordinate



x coordinate

Performance of conventional chemically amplified resists –Resolution-

Acid image resolution (acid diffusion length does not depend on wavelength)

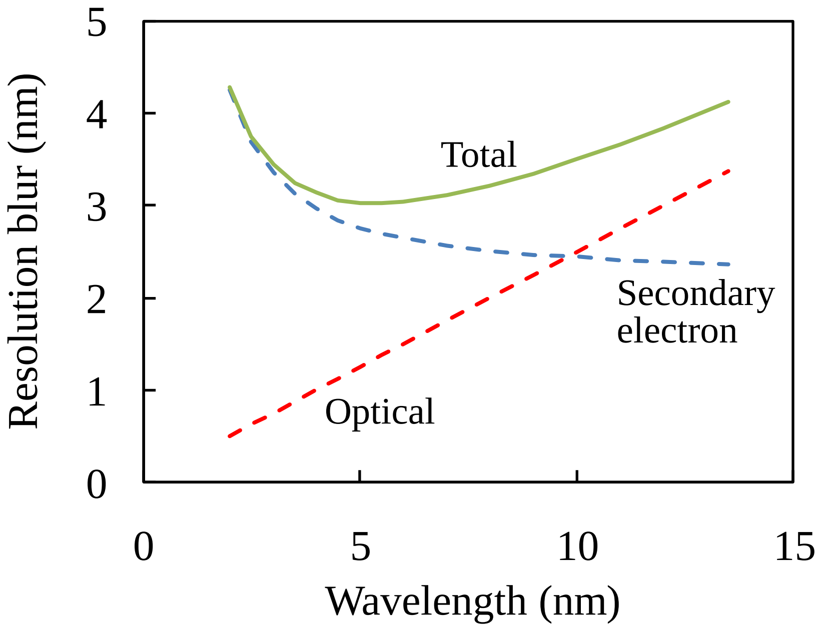
Optical blur, b_{optical}

$$b_{optical} = \frac{CD}{2} \qquad CD = k_1 \frac{\lambda}{NA}$$

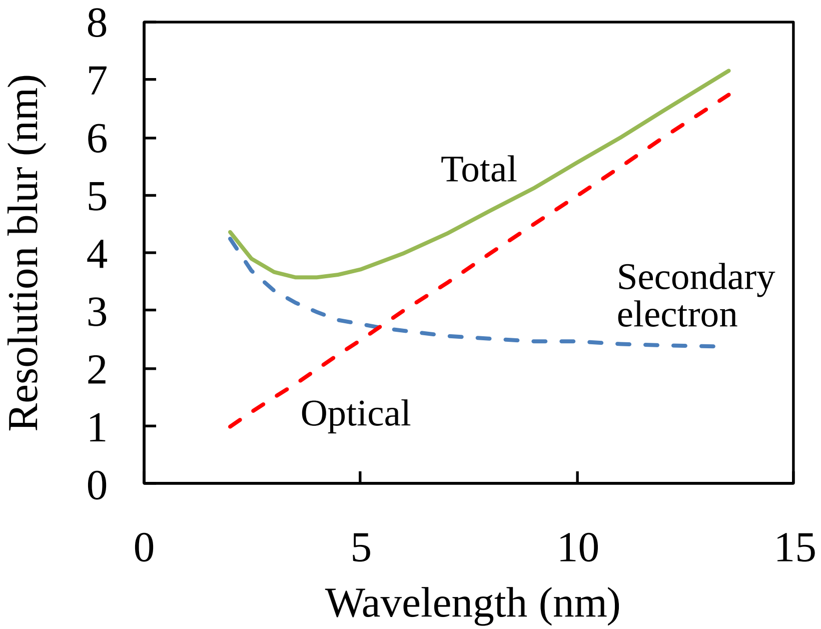
Secondary electron blur, b_{electron}

Average distance

Total blur, $b_t = \sqrt{b_{optical}^2 + b_{electron}^2}$



$$\frac{k_1}{NA} = 0.5$$



$$\frac{k_1}{NA} = 1$$

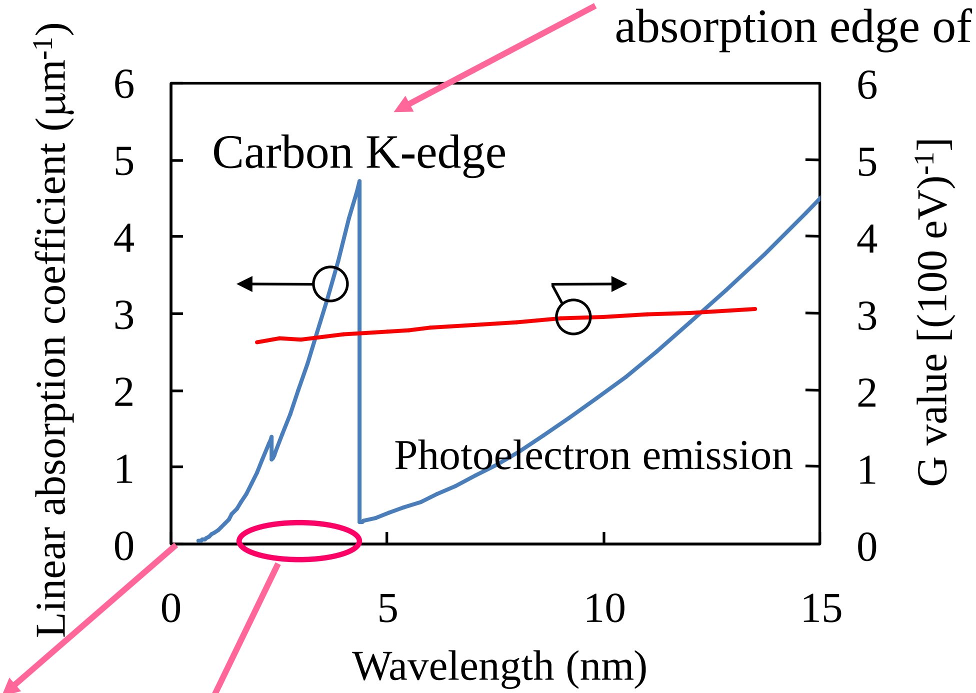
Performance of conventional chemically amplified resists –Sensitivity-

Acid concentration (acid diffusion length does not depend on wavelength)

Absorption coefficient

Acid generation efficiency per unit absorbed dose (G value)

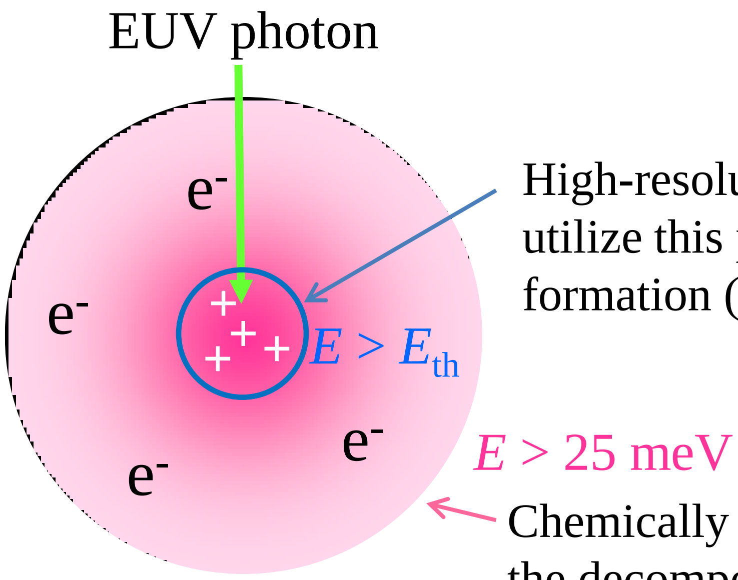
The W-value increases by 10-20% at the absorption edge of the inner shell.



Compton scattering

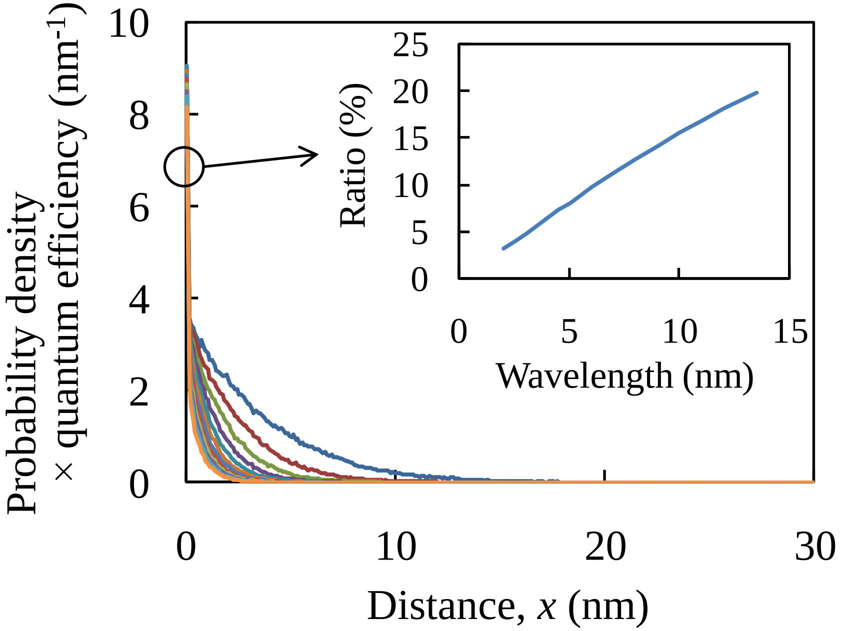
Inner shell excitation
- Auger electron (light element)
  - Positively affect resolution
- Fluorescence X-rays (heavy element)
  - Negatively affect resolution

Non-chemically amplified resists

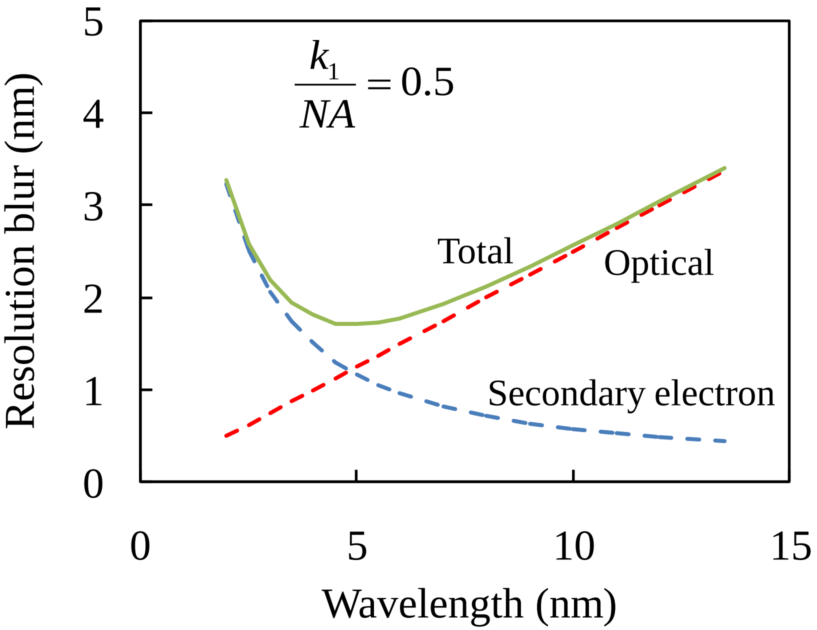


High-resolution conventional resist such as PMMA utilize this part for the chemical reaction for pattern formation (main chain scission).

Chemically amplified resists utilize this part for the decomposition of acid generators.



Distribution of radical cation



Resolution blur of L&S pattern

Summary

The wavelength dependence of lithography resolution was investigated in the wavelength region of extreme ultraviolet. The resolution is expected to be highest at a wavelength of 3-5 nm, depending on NA of exposure tools. In the case of low-NA tools, the merit of wavelength reduction from 13.5 nm is significant. However, the merit of wavelength reduction is lost in the case of high-NA tools, particularly when the increase in transparency of the resist with the reduction in wavelength is taken into account.

Acknowledgement

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